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Numerical evaluation of mechanical behaviour of lattice structures for rotating blades

İnci Pir[1]*, Serhat Arda Şahin[1], Mertol Tüfekci[2,3], and Ekrem Tüfekci[1]

[1] Faculty of Mechanical Engineering, Istanbul Technical University, Beyoğlu, Turkey
[2] School of Physics Engineering and Computer Science, University of Hertfordshire, Hatfield, AL109AB, UK
[3] Center for Engineering Research, University of Hertfordshire, Hatfield, AL109AB, UK

Abstract: Lattice structures have significant potential in engineering, allowing for material and weight reduction while maintaining desired mechanical properties. This versatility is crucial in applications ranging from aerospace to medical implants, where customisability and efficiency are essential. This study investigates the mechanical performance of four lattice structures with multiple and single-cell model approaches. The aim is to elucidate the impact of lattice design parameters on the structural integrity and performance of components subjected to dynamic loads typical of rotating blades in aerospace applications. Utilising Finite Element Analysis (FEA), this research is conducted to characterise the overall mechanical behaviour and to simulate the behaviour of these structures under conditions that represent real-world operational conditions for rotating blades. The loading conditions considered are tension, compression, shear and periodic boundary conditions are applied. By comparing the mechanical behaviour of these lattice structures against each other, this research aims to identify optimised lattice designs that enhance the performance and durability of rotating blades. This study is expected to contribute to the broader field of materials science and engineering by providing guidelines for designing more efficient, lightweight, high-performance components in various industrial applications.

Keywords: Lattice Structures, Finite Element Analysis (FEA), Mechanical Behaviour, Periodic Boundary Conditions, Specific Stiffness

1 Introduction

The use of lattice structures is becoming more common day by day. A lattice structure is a repeating geometric arrangement of points in space, crucial for determining a material's properties. Lattice structures offer flexibility in designing complex geometries while reducing weight. Lattice structures are complex geometries that provide engineering advantages such as reduced weight, increased strength, enhanced energy absorption, and improved thermal properties Gibson and Ashby (1997).

Lattice structures have a wide range of applications in the aerospace, automotive, biomedical and energy fields Ashby (2006); Egan et al. (2019); Wang et al. (2017a); Hussain et al. (2022a); Boursier Niutta et al. (2022). These structures offer significant advantages in applications requiring lightness and high strength. In impact absorption cases, they can be used for rotating components like blades Van Der Merwe et al. (2022); Wang et al. (2017b); Hussain et al. (2022b). In the aerospace, railway and automotive sectors, they are preferred in crash safety systems due to their energy absorption capacity Boursier Niutta et al. (2022); Hou et al. (2023); Khan and Riccio (2024); Meran et al. (2016). For example, in the biomedical field, they are used as ideal scaffold materials for tissue engineering applications and tumour resection studies Zein et al. (2002); K. C. Wong and Demol (2015).

Auxetic structures, which exhibit a negative Poisson's ratio, expand laterally when stretched and contract when compressed Evans and Alderson (2000). This unique behaviour enables them to distribute impact forces more effectively by enhancing energy absorption Lakes (1987). Their high fracture resistance and strength contribute to their durability Junio et al. (2023). Owing to their capacity to create lightweight structures, auxetic materials are favoured in applications requiring weight reduction, such as in aircraft and satellites. They hold significant potential in areas demanding resistance to extreme conditions and dynamic shape changes. In rotating systems, auxetic structures have considerable potential to enhance structural performance Kolken and Zadpoor (2017). They are particularly useful in areas like aerospace, wind turbines, and the defence industry Kelkar et al. (2020). By increasing resistance to impact under high load and vibration conditions, these materials improve the long-term durability of rotating structuresLira et al. (2011). Their vibration-damping properties also enhance vibration and acoustic performance SCARPA and TOMLINSON (2000)Evans and Alderson (2000). Additionally, when used rotating blades, auxetic structures offer substantial structural advantages due to their strength, lightness and durability Junio et al. (2023)Kelkar et al. (2020).

Lattice structures have complex geometries, and the manufacturing of complex geometries is a challenging process when traditional manufacturing methods are used. 3D printing technologies address this challenge and facilitate the manufacturing and utilisation of lattice structures on a larger scale. Within the common usage of lattice structures, mechanical properties studies on lattice structures gained interest day by day. While designing a structure, determining its mechanical behaviour plays a significant role in terms of its life cycle.

The mechanical behaviour of lattice structures varies depending on the applied loading conditions, lattice geometry, manufacturing method of lattice structures and material properties. Determining the mechanical properties of lattice structures is critical

* E-mail address: pirin@itu.edu.tr

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to optimising their performance and developing suitable designs for specific applications. There are several ways to define the mechanical behaviour of lattice structures. Experimental methods, numerical simulations, theoretical models, and hybrid approaches are widely used Egan et al. (2019); Beyer and Figueroa (2016); Niu et al. (2017); Meram and Çetin (2020).

One of the most common methods for determining the mechanical properties of lattice structures is experimental methods Zhu et al. (2024). Standard mechanical tests such as tension, compression, bending, buckling, and impact tests measure the strength, stiffness, and deformation behaviour of lattice structures Al Khalil et al. (2021); Lei et al. (2021); Bisoi et al. (2023). Experimental studies conducted by standards such as ASTM and ISO play a critical role in verifying the mechanical performance of lattice structures ASTM International (1991); International Organization for Standardization (2011). Due to these structures exhibiting different mechanical behaviours under tension, compression, and in-plane shear loading, several experimental methods are used to determine the mechanical behaviour of lattice structures Boursier Niutta et al. (2022); Duraibabu et al. (2020).

In addition to experimental studies, numerical simulation methods are also widely used to understand the mechanical properties of lattice structures. In particular, FEA is one of the preferred numerical tools for modelling and optimising the behaviour of lattice structures Messner (2016); Gorguluarslan (2021). FEA is used to simulate how lattice structures behave under various loading conditions (tension, compression, buckling, etc.). FEA can predict the strength, deformation, and collapse behaviour of structures. It also allows optimisation for different cell geometries and material properties Daxner (2010).

Theoretical models and analytical methods are also used to predict the mechanical properties of lattice structures. These models mathematically analyse the mechanical behaviour of lattice structures Sing et al. (2018).

Hybrid approaches, where experimental, numerical and theoretical methods are used together, are also widely used in determining the mechanical properties of lattice structures Teng et al. (2022); Dar et al. (2020); Partovi Meran et al. (2014). Verification of experimental data with numerical simulations and comparison with theoretical models provide more reliable results. Especially in critical applications, the performance of lattice structures can be optimised with hybrid methods.

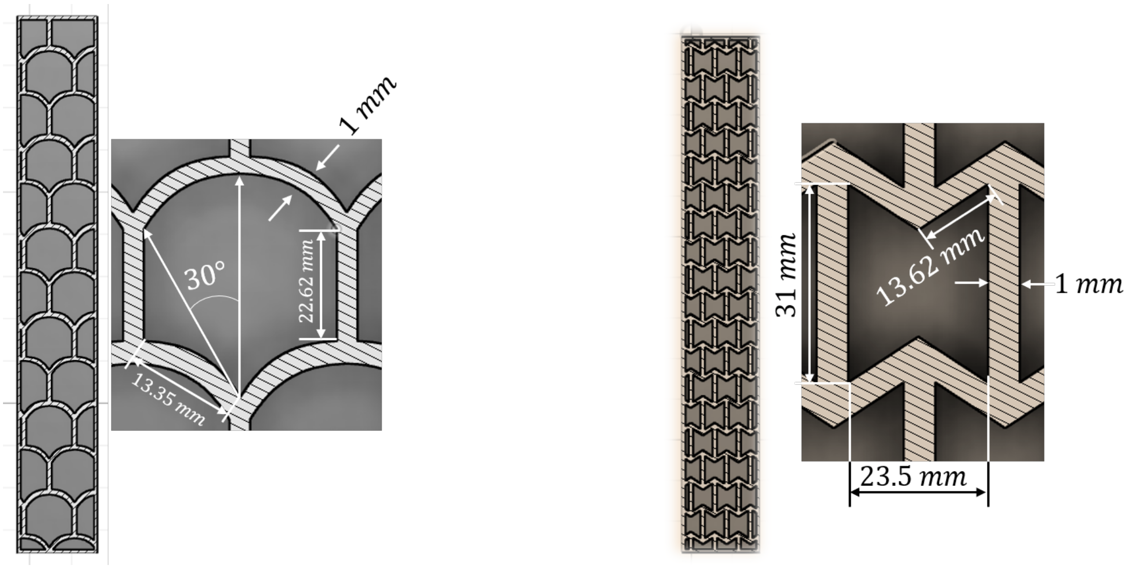
When modelling lattice structures with FEA, single-cell and multiple-cell approaches are generally utilised Montoya-Zapata et al. (2020); Bergmann and Merkert (2018). With the single-cell approach, only one cell (the basic unit of the lattice structure) is modelled, and the analysis is performed on this cell. This approach is used in cases where the entire lattice structure consists of periodically repeating unit cells. In the single-cell approach, the unit cell is modelled, boundary conditions are applied, and the results are generalised to the entire structure. The advantages of this approach include low computational cost and providing simple and fast solutions for repeating structures. In the multiple-cell approach, the structure is modelled with multiple cells by combining them and performing the analysis on that larger structure. Lattice structures may not be homogeneous, or local effects may be desired to be examined in certain areasStrömberg (2020). In this case, a larger area containing more than one cell is modelled. This approach produce**s**/yield**s** better results for irregular or complex structures and can more accurately simulate local effects and boundary conditions. However, the computational cost is high, and the modelling process is more complicated.

In this study, it is aimed to examine the mechanical behaviour of the complex geometries. There is a need for lightweight, rigid structures in rotating components due to centrifugal forces. Firstly, four different lattice geometries with single and multiple-cell assumptions are generated using computer-aided software. Then, they are subjected to tension, compression and in-plane shear loading using FEA with periodic boundary conditions (PBC).Results of each geometry and cell type are compared and given in this study.

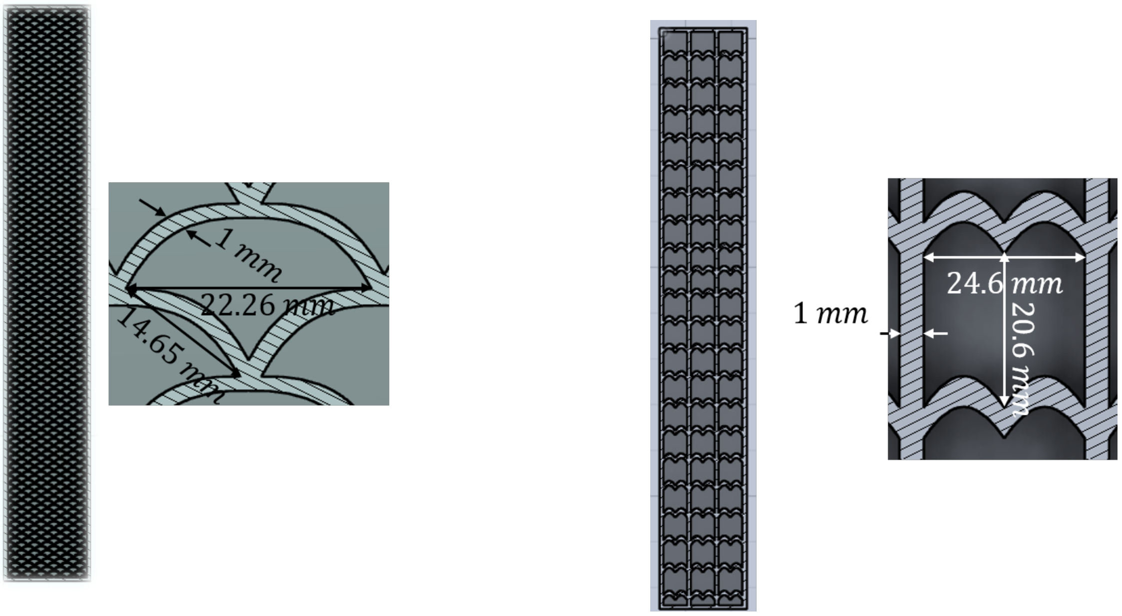
Within the scope of this study, a comprehensive analysis of the Finite Element Method (FEM) for modelling different geometries under PBC is presented, single-cell and multi-cell models are employed, and various loading types are considered. The behaviours of single-cell and multi-cell models in response to various load types are compared. The application of PBC in single-cell and multi-cell models allows a better understanding of the mechanical responses under different load types. This comprehensive analysis provides a better understanding of the strengths and limitations of the modelling procedures and offers important implications for practical applications, especially in material design and analysis, and provides an innovative contribution to the field.

2 Computational Modelling and Analysis

In this study, different types of lattice structures with single-cell and multiple-cell models under various loading conditions are evaluated. Four diverse cellular structures are selected to ensure uniform unit cell dimensions within this aim. Geometries of these lattice structures are selected from the literature Mukherjee and Adhikari (2021); Adhikari (2021); Mukherjee et al. (2023); Mukherjee and Adhikari (2022) and modelled using computer-aided design software. The most important point to consider in the created geometries is that the individual cells of each structure are designed with similar geometric dimensions so that they can be compared with each other, ensuring unit cell dimensions. By keeping the in-plane length of each auxetic structure the same, the width and other parameters of the structure are aimed at keeping the same. Unit cell structures are named AUX1, AUX2, AUX3, and AUX4. Unit cell dimensions, names of the geometries and geometrical details of each geometry are given in Figure 1.



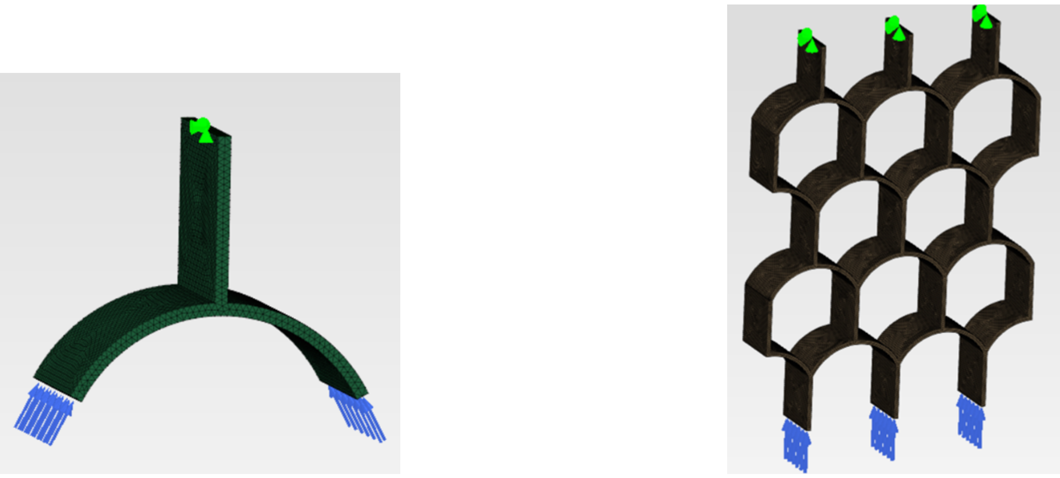
(a) AUX1 (b) AUX2



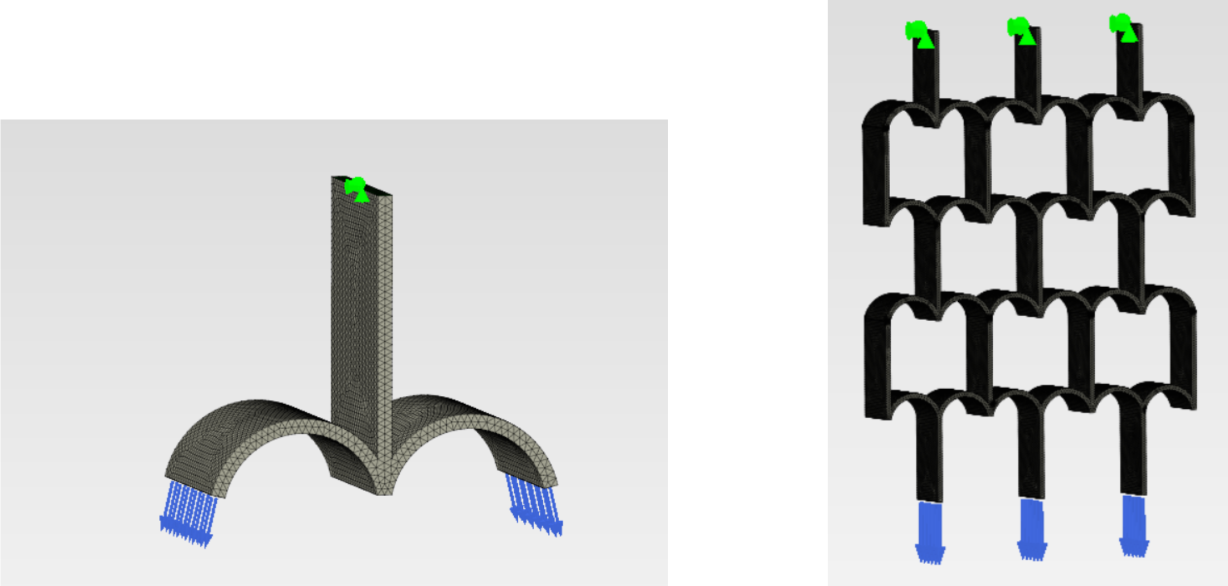
(c) AUX3 (d) AUX4

Fig. 1: Geometrical details and unit cell dimensions of evaluated geometries.

It is mentioned that single and multiple-cell models are evaluated with FEA. For this purpose, single and multiple-cell geometries are modelled using computer-aided design software and subjected to loading. In the multiple-cell structure, a similar arrangement as in the single-cell structures is applied. For single-cell structures, the smallest unit representing the geometries shown in Figure 1 is used. To ensure PBC and allow the system to repeat periodically, the single cells are connected in a way that maintains this periodicity. Within this aim, the multi-cell structure consists of single cells arranged in a 3-2-3 pattern, which is the number of cells in each row in the multi-cell structure, as shown in Figure 2-b and d. The system is evaluated in terms of the movement and rotational freedoms. Translational motion of the boundary surfaces is unconstrained on the model, while rotational freedom is permitted within the system. Three different loading models are created for each single and multiple-cell structure. These models are developed according to tensile, compressive and in-plane shear forces, and 12 different models are obtained. While modelling the forces acting on cellular structures, pressure-type force spreading to the surface on which the force acts is applied to tensile and compressive forces. In the in-plane shear force, a point that is symmetrical to the surfaces on which the force will affect/will not create extra stress is determined as the reference point, and this point and the surfaces are defined by each other as a rigid body. In this way, it is aimed to spread the shear force homogeneously to the surfaces. In Figure 2, pictures of FEA models of single and multiple-cell structures are presented.



(a) Single-cell compression model (b) Multiple-cell compression model



(c) Single-cell tension model (d) Multiple-cell tension model

Fig. 2: Single and multiple cell models, loading and boundary conditions.

The selected boundary conditions of tension, torsion, shear, and rotation around an axis perpendicular to the beam's main axis are highly relevant to the operational conditions experienced by rotating blades. In practical applications such as turbines, helicopter rotors, and aerospace propulsion systems, rotating blades are subjected to complex loading scenarios that encompass these specific forces. Tension arises from centrifugal forces due to high-speed rotation, inducing significant stress along the blade's length, which can affect structural integrity and fatigue life. Torsional loads result from aerodynamic twisting moments and mechanical interactions within the rotor assembly, influencing the blade's angle of attack and overall aerodynamic performance. Shear stresses occur due to transverse forces from airflow and pressure differentials across the blade surfaces, potentially leading to deformation or failure if not properly managed.

Additionally, rotation around an axis perpendicular to the beam's main axis is crucial for capturing gyroscopic effects and dynamic stability concerns that are inherent in rotating machinery. This aspect is essential for understanding how the blade responds to off-axis forces and moments, which can impact vibration characteristics and resonance behaviour. By applying these boundary conditions in the finite element analysis, the study effectively simulates the real-world mechanical environment of rotating blades. This comprehensive approach ensures that the evaluation of the lattice structures considering mass and stiffness at the same time as the blade is subjected to aero-pressure loads and centrifugal body forces that are related to their mass, thereby providing meaningful information about their suitability, performance, and reliability in aerospace applications.

These models are modelled with an open-source FEM software package PrePoMax.Acrylonitrile Butadiene Styrene (ABS) with 2000 MPa Young Modulus and 0.38 Poisson's ratio is selected as material for models. These models are modelled with tetrahedral mesh. Details of the element sizes are given in Table 1.

Tab. 1: Element size table

Maximum element size	0.5 mm
Minimum element size	0.01 mm
Elements per edge	2

PBC are used to model an infinite material or system by repeating a small representative unit. For a single cell, PBC ensures that the behaviour on one side of the cell is mirrored on the opposite side. This requires that the displacements, forces, or other physical quantities at the cell boundaries be consistent between adjacent cells. Single cell PBC makes calculations by simulating a small region that represents the behaviour of the entire system, assuming that the material is homogeneous.

By using multiple cells, interactions between neighboured cells are considered and the behaviour of the material over a larger region is modelled more accurately. PBC is useful for understanding local mechanical effects. Effects such as local stresses or deformations can be studied under PBC and related to the macroscopic behaviour of the entire system, contributing to the understanding of the overall performance of the material.

PBC are used in the finite element method to study the load and displacement behaviour of repeating structures. These conditions ensure that a small representative unit cell (RVE) behaves as if it were part of a larger structure. PBC simulate the behaviour of an infinite structure by ensuring that the loads applied to nodes on one edge of a structure are repeated in the same manner on the other edges. In terms of load distribution, PBC provide accurate load distribution and stress analysis depending on the homogeneous or heterogeneous structure of the material. Especially in composite materials, this method minimizes edge effects and ensures that the load is distributed homogeneously throughout the entire structure.

As input, junction points of lattice structure are subjected to periodic boundary conditions and 0.1 N load, as the literature presents Mukherjee and Adhikari (2021)Adhikari (2021)Mukherjee et al. (2023)Mukherjee and Adhikari (2022). In Table 2, the description of loading types is presented.

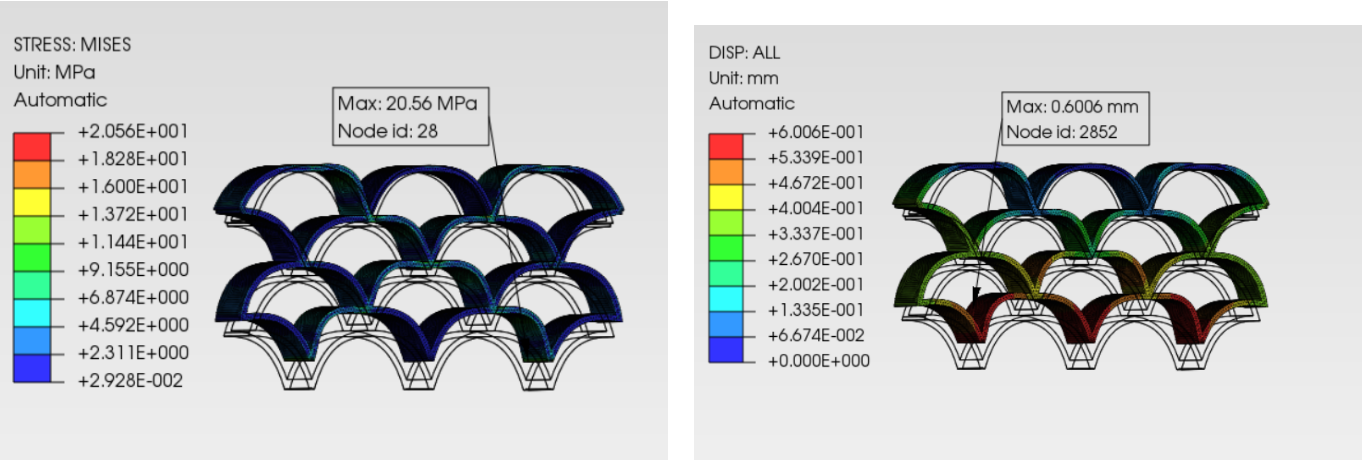
Tab. 2: Description of applied loads

Loading Type	Applied Load [N]
Compression	0.1
Tension	0.1
Shear	0.1

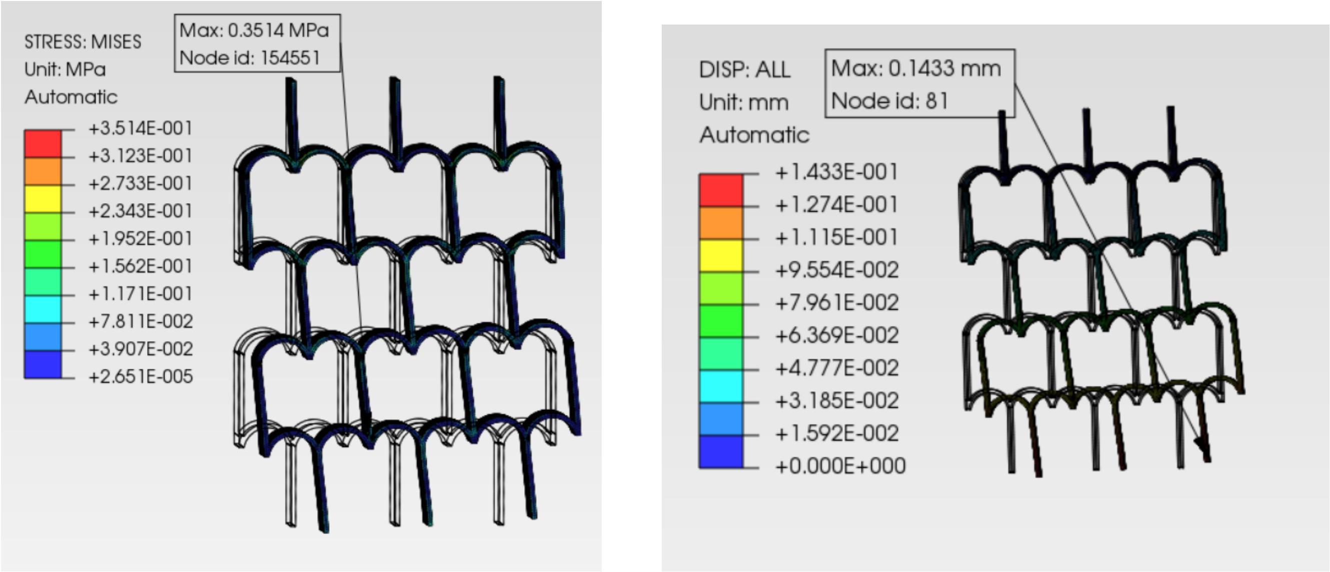
As output, it is aimed to get maximum displacements, which give information about the structure's rigidity, and von Mises stress distributions, which ensures that the FEM model does not contain extreme discontinuities and remains accurate.

3 Results and Discussion

Results of the FEA study for each lattice structure according to loading type and cell structure are given in this section. In Figure 3, von Mises stress distribution and maximum displacements belonging to the multiple-cell model of aux are given. From that figure, it can be clearly said that the stress distribution is continuous and realistic, and there is no extreme stress concentration.



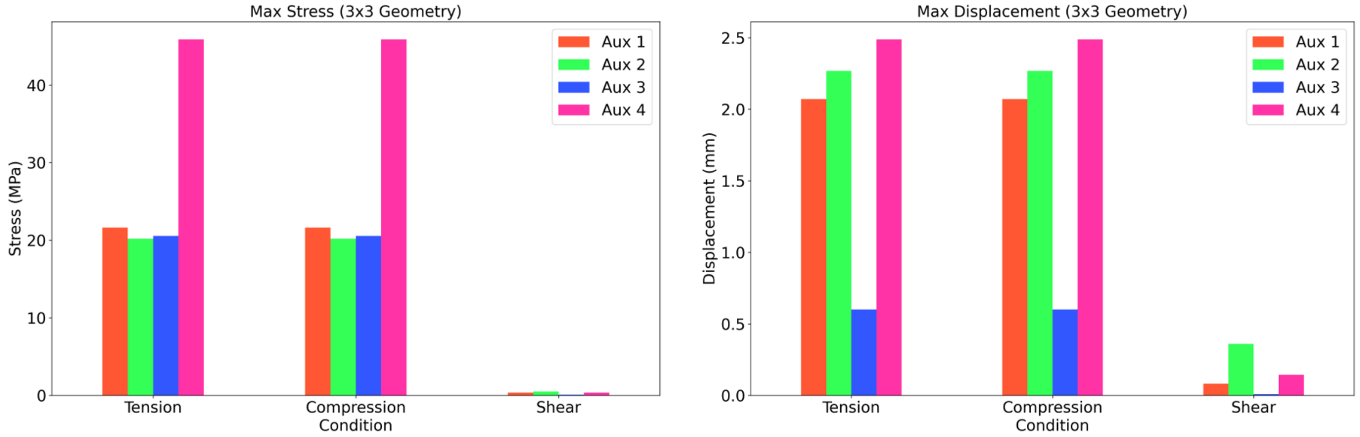
(a) Stress distribution (b) Maximum displacement distribution



(c) Stress distribution (d) Maximum displacement distribution

Fig. 3: Von Mises stress distribution and maximum displacements of multiple cell model.

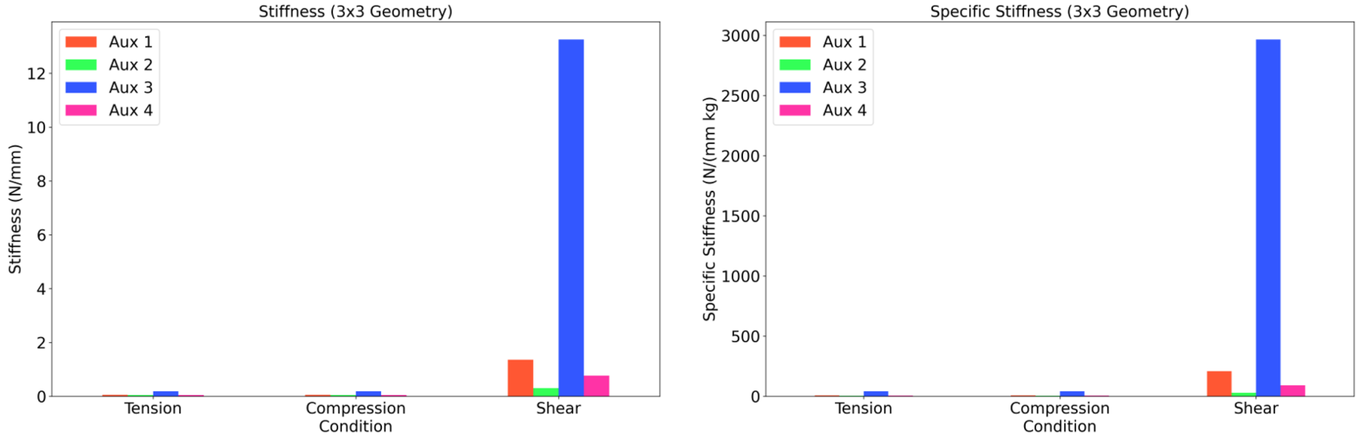
Maximum stress and displacement values for multiple cell structures according to the lattice geometry are expressed with bar graphs, and they are given in Figure 4. It is seen from the figures that tension and compression values are similar. Since the material making up the lattice structure is taken as linear elastic, the structure has no effect on changing this linear elastic situation.



(a) Maximum stress (b) Maximum displacement

Fig. 4: Maximum stress and displacement values according to loading and lattice type in multiple cell structures.

With FEA steps, stiffness and specific stiffness (stiffness with respect to mass) of each lattice structure with multiple cell model is calculated and given in bar graphs in Figure 5.



(a) Stiffness (b) Specific stiffness

Fig. 5: Stiffness and specific stiffness values according to loading and lattice type in multiple cell structures.

The stiffness and specific stiffness results for the multiple-cell structures reveal notable differences in mechanical performance among the lattice geometries under various loading conditions.

The AUX1 lattice exhibits the highest stiffness under tensile and compressive loads among all the evaluated geometries. This superior performance can be attributed to its straightforward and orthogonal design, which provides a direct load path and uniform material distribution along the loading direction. The rectilinear configuration minimises deformation under axial loads, resulting in higher stiffness values. However, under in-plane shear loading, the AUX1 structure shows relatively lower stiffness due to its limited ability to redistribute shear stresses effectively.

The AUX2 lattice, characterised by its re-entrant honeycomb geometry, demonstrates enhanced performance under shear loading compared to tension and compression. The negative Poisson's ratio of auxetic structures like AUX2 allows them to expand laterally when stretched, improving shear resistance. The geometric configuration enables efficient stress dissipation across the hexagonal cells, making it more adaptable to shear deformation. Nonetheless, the increased flexibility of the structure results in lower stiffness under axial loads.

The AUX3 lattice, with its curved cell geometry, offers a balance between stiffness and flexibility. Its curved elements facilitate better load transfer and distribution under axial and shear loads. The geometry promotes structural compliance, allowing for moderate deformation while maintaining structural integrity. This results in intermediate stiffness values across all loading conditions. The curved design also contributes to improved resistance against bending and torsional stresses.

The AUX4 lattice presents a complex geometry with interconnected cells, providing enhanced stiffness under shear loading. The intricate network of struts and nodes allows for efficient stress redistribution, leading to higher shear stiffness. However, similar to AUX2, the increased complexity and flexibility of the structure reduce its stiffness under tensile and compressive loads compared to AUX1.

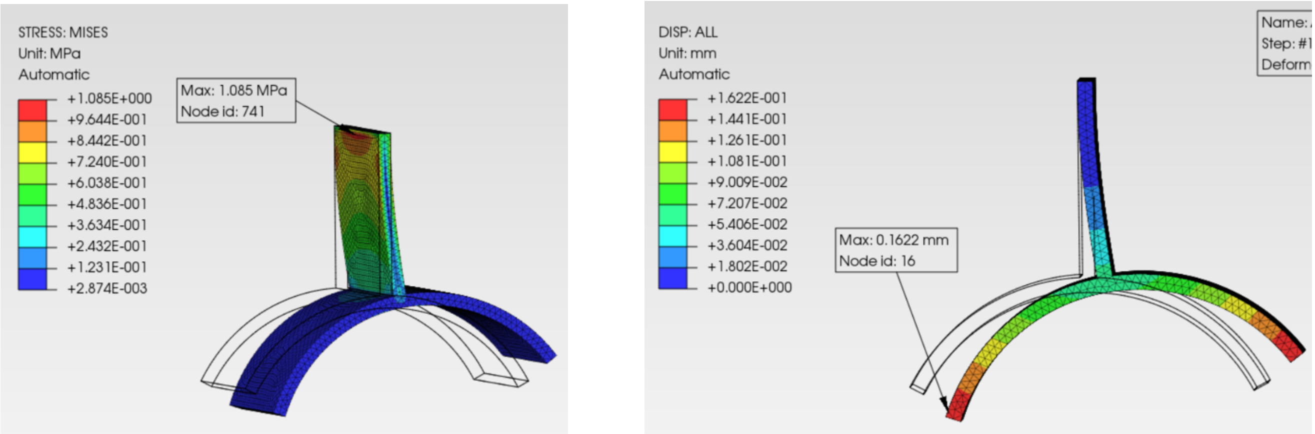
The observed differences in mechanical performance can be explained by the unique geometric features of each lattice structure.

Structures like AUX1 with uniform material distribution along the load paths exhibit higher stiffness under axial loads. In contrast, geometries with more open or complex cell configurations (AUX2, AUX3, AUX4) distribute material differently, affecting their load-bearing capabilities.

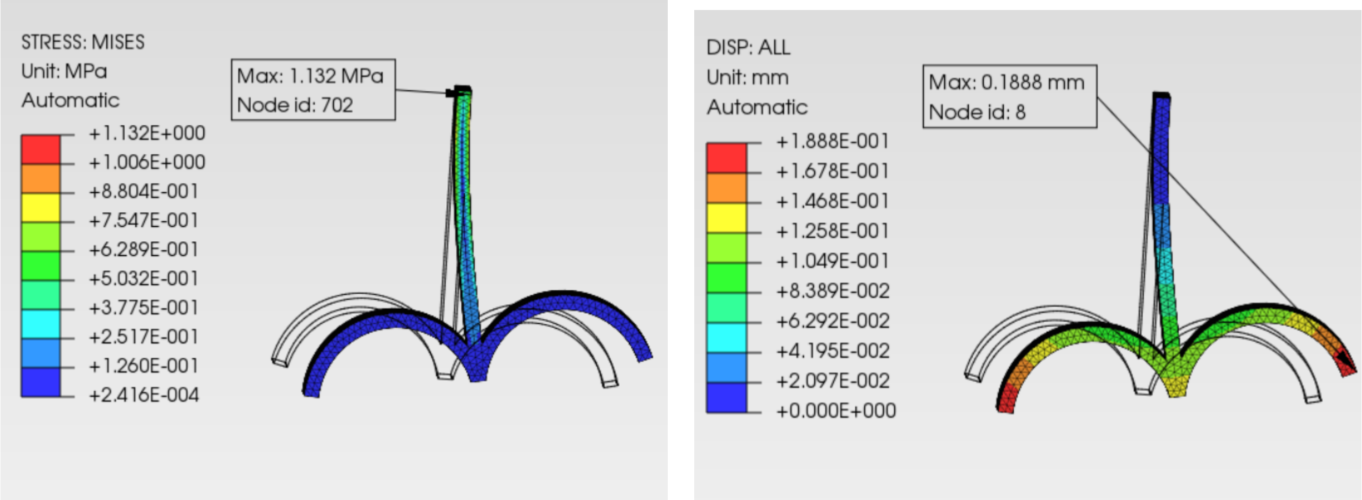
The connectivity and orientation of cells influence how loads are transferred and distributed. Auxetic structures (AUX2) expand laterally under tension, enhancing shear resistance but reducing axial stiffness. Curved geometries (AUX3) allow for better accommodation of deformations, providing a compromise between stiffness and flexibility.

The specific stiffness results highlight the efficiency of each structure in terms of stiffness-to-mass ratio. Structures with lower mass but efficient load distribution (e.g., AUX3) may offer higher specific stiffness, which is advantageous in applications where weight savings are critical.

The same procedure is applied to single-cell structures as to multiple-cell structures. Von Mises stress distribution and maximum displacements are drawn and given in Figure 6. Similar to the findings from the multiple-cell model, the stress distribution is continuous and realistic, and no extreme stress concentration is seen.



(a) Stress distribution (b) Maximum displacement distribution

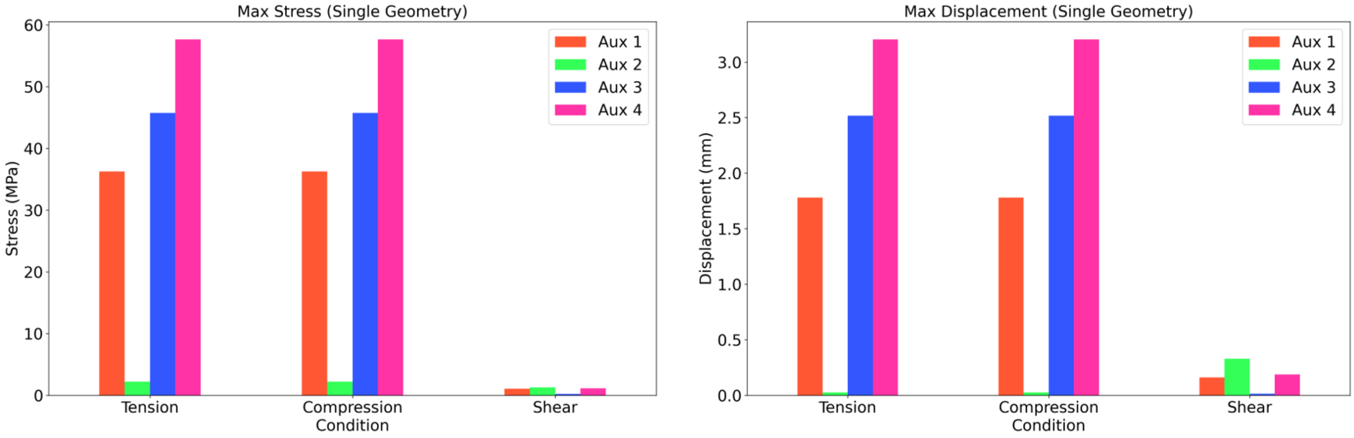


(c) Stress distribution (d) Maximum displacement distribution

Fig. 6: Von Mises stress distribution and maximum displacements of single-cell model.

Stress behaviours for both single-cell and multi-cell cases are obtained through FEM analysis. From the results of FEM analysis, it is observed that compressive and tension stress values are dominant in these geometries. This behaviour can be correlated with beam theories, which primarily focus on compressive and tensile stresses rather than shear effects. In beam models, shear stresses are primarily observed in the central region, while the maximum stress values, including compressive and tensile stresses, occur in the top and bottom zones of the beams. Additionally, when the stress distributions over the cell geometries are investigated maximum stress zones are tend to be observed at the top and bottom zones which can be attributed to the stress behaviour of beams. Based on these approaches, it can be concluded that modelling these geometries using beams rather than three-dimensional solid elements is both accurate and efficient. In addition to accuracy and efficiency, the beam modelling approach leads to an optimal solution by significantly reducing the computational costs and loads compared to 3D solid elements.

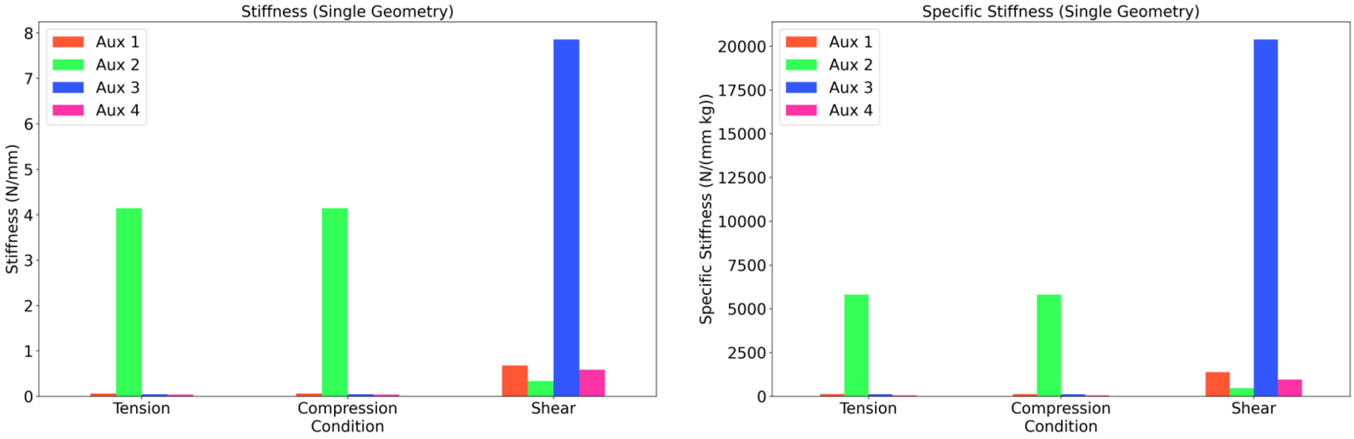
From FEA results, maximum stress and displacement values for multiple cell structures according to the lattice geometry can be obtained, and the results are arranged as bar plots. Maximum stress and displacement values due to tension, compression, and in-plane shear for a single-cell case in each lattice geometry are given in Figure 7. From that Figure, it can be said that single-cell results do not match multiple-cell results.



(a) Maximum stress (b) Maximum displacement

Fig. 7: Maximum stress and displacement values according to loading and lattice type in single-cell structures.

In order to compare, stiffness and specific stiffness values for each lattice geometry in single-cell geometry are calculated and given in Figure 8.



(a) Stiffness (b) Specific stiffness

Fig. 8: Stiffness and specific stiffness values according to loading and lattice type in single-cell structures.

In the single-cell models, the mechanical responses differ notably from the multiple-cell counterparts. The discrepancies highlight the impact of cell interactions and boundary conditions on the overall mechanical behaviour of lattice structures.

The single-cell AUX1 model retains relatively high stiffness under axial loads, similar to the multiple-cell model. Its simple geometry does not rely heavily on interactions with adjacent cells, making its performance less sensitive to the cell arrangement.

The AUX2 single-cell model shows a significant reduction in stiffness compared to the multiple-cell model. The auxetic behaviour and mechanical advantages of the re-entrant geometry rely on the collective deformation of multiple cells. The single-cell model cannot fully exhibit its characteristic mechanical properties without adjacent cells to facilitate lateral expansion.

The performance of the AUX3 single-cell model decreases in stiffness due to the lack of neighbouring cells that contribute to its load-bearing capacity. The curved elements depend on the continuity provided by multiple cells to distribute stresses effectively.

Similar to AUX2 and AUX3, the AUX4 single-cell model exhibits reduced stiffness. The complex interconnected geometry relies on the presence of multiple cells to achieve structural integrity and effective stress redistribution.

The single-cell models may not accurately capture the mechanical behaviour due to the limitations of applying periodic boundary conditions to a single-unit cell. The interactions between cells, crucial in multiple-cell lattices, are absent, leading to discrepancies in stiffness and displacement responses.

Structures with geometries that inherently rely on adjacent cells (AUX2, AUX3, AUX4) demonstrate diminished performance when modelled as a single cell. This underscores the importance of considering multiple-cell arrangements to assess the mechanical properties of such lattices accurately.

Since the cell is a repeating small element and periodic boundary conditions represent the periodicity and boundary conditions of the smallest element, they should represent the properties of the entire system. As a result, local effects are also expected to be observed within these cells. This allows for the overall displacement and stress distributions to be captured. Consequently, the overall displacement and stress distributions can be evaluated, but these results reflect the general distribution. However, while these results provide a general distribution, the outcomes from the single-cell approach do not align with those from the multi-cell approach and the local effects could not be observed.

Differences in the results of single and multiple-cell structures may be due to the insufficiency of the periodic boundary conditions to represent the actual behaviour. This study presents that periodic boundary condition assumption should be re-evaluated for single-cell cases. Therefore, the results show that each lattice structure behaves differently under the same loading type. This shows the mechanical behaviour variability of the lattice structures.

The performance differences among the lattice structures under various loading conditions emphasise the critical role of geometric design in determining mechanical behaviour. The selection of an appropriate lattice geometry depends on the specific performance requirements of the application. Applications requiring high stiffness under axial loads may benefit from lattices like AUX1, with straightforward geometries that provide direct load paths. In contrast, applications where energy absorption and flexibility are desired, such as impact mitigation, may find structures like AUX2 and AUX3 more suitable due to their ability to deform and absorb energy. Structures like AUX2 and AUX4 exhibit enhanced shear resistance due to their geometric configurations that facilitate stress redistribution under shear loading. This makes them advantageous in applications where shear loads are predominant. The specific stiffness results highlight the importance of considering mass in lattice design. Structures that offer high stiffness-to-mass ratios are beneficial in aerospace applications where weight savings are crucial. Understanding the relationship between lattice geometry and mechanical performance enables optimising structures tailored to specific loading conditions and performance criteria. Designers can leverage the unique properties of different lattice geometries to achieve desired outcomes, whether maximising stiffness, enhancing energy absorption, or reducing weight.

4 Conclusion

Lattice structures are defined as elements that have a cellular structure and generally offer lightness and high-strength properties. The mechanical behaviour of lattice structures under different loading conditions has been extensively studied in the literature. The mechanical behaviour of lattice structures is closely related to their geometry and the materials used. The mechanical properties of lattice structures can be optimised with the kind of material used and the cell structure. For example, while metallic lattice structures offer high strength and energy absorption properties, polymeric lattice structures are lighter and can absorb energy by showing more deformation at the moment of impact. Depending on the geometry of the lattice structure, different mechanical behaviours can be observed, and the most appropriate selection can be made. These characteristics enable lattice structures to be utilised in a wide variety of applications.

In this study, the mechanical behaviour of four different lattice structures is evaluated with FEA. Three different loading conditions are applied to the single- and multiple-cell models with periodic boundary conditions, and each geometry is subjected to the same loading and boundary conditions. As a result, stresses regarding loading, stiffness, the von Mises stress distributions and maximum displacements of each geometry are obtained. Results of multiple and single-cell models do not overlap, which shows the need to re-arrange periodic boundary conditions.

The notable difference between the results of single-cell and multi-cell lattice structure models is primarily related to the limitations in the representation capability of the PBC used in the simulations. Periodic boundary conditions are intended to simulate an infinite lattice by repeating a single unit cell's behaviour throughout space. However, when applied to a single-cell model, PBC may not sufficiently capture the complex interactions and collective behaviour that occur in an actual multi-cell lattice structure. In single-cell models, the PBC assume that the cell is surrounded by identical cells extending infinitely, which can oversimplify the stress distributions and deformation patterns, especially under complex loading conditions. This simplification may neglect edge effects, local variations, and interactions between multiple cells that are significant in determining the mechanical response of the structure. As a result, single-cell models with PBC might yield results that deviate from those obtained from multi-cell models, which inherently account for these interactions due to their larger size and inclusion of multiple cells.

If the periodic boundary conditions were entirely sufficient, both single-cell and multi-cell models would produce similar results. The observed differences suggest that the PBC, as implemented, may not fully represent the actual behaviour of the lattice structures under study. Enhancing the representation capability of the PBC could involve modifying them to better account for the interactions between cells or increasing the number of cells in both the x and y directions to minimise the influence of boundary approximations. So, the difference between the results between single-cell and multi-cell models highlights the need to revisit the periodic boundary conditions used in the simulations. By refining these conditions or employing larger multi-cell models, the simulations can more accurately reflect the true mechanical behaviour of the lattice structures. This approach would improve the validity of the results and provide more reliable insights into the performance of the materials under various loading conditions.

In future research, several areas could be explored to build upon the findings of this study. First, further investigation into the optimisation of boundary conditions for single-cell lattice models is necessary, particularly in improving the accuracy of periodic boundary assumptions. Additionally, incorporating different materials beyond linear elastic assumptions would provide a broader understanding of how material properties influence the mechanical performance of lattice structures. Experimental validation of the numerical results, including tests under real-world operational conditions, could also strengthen the conclusions drawn from this study. Finally, expanding the scope of the research to include non-periodic or hybrid lattice designs and investigating their effects under dynamic and multi-axial loading conditions could lead to more efficient and robust structural solutions, particularly in aerospace and other high-performance engineering applications. In addition to the finite element analysis conducted in this study, future work could benefit from exploring the modelling of lattice structures as beams. This approach would allow for the derivation of analytical solutions that could predict both the modal behaviour and the static response of these structures under various loading conditions. By treating lattice structures as beams and frames, simplified models could be developed to estimate natural frequencies, mode shapes, and deflections under static loads, providing valuable insights into their dynamic and structural performance. Analytical models would also complement the numerical simulations, offering faster and potentially more generalised predictions that could be used during the preliminary design stages of lattice-based components. Such an approach could enhance the optimisation process for applications where dynamic stability and stiffness are critical, such as rotating blades in aerospace systems.

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